CHAPTER 10
AN OVERVIEW OF GAS TURBINES

INTRODUCTION

Gas turbines are used in a wide range of services.[1,2] They power aircraft of all types and drive mechanical equipment such as pumps, compressors, and generators in electric utilities. They also generate power for peak loads and base-load duties. Recently, the interest in gas turbines has grown significantly in combined-cycle plants. These plants use combinations of gas and steam turbines in various configurations of turbines, heat recovery steam generators, and regenerators.

Gas turbines have these advantages over steam plants:

- They are small in size, mass, and initial cost per unit output.
- Their delivery time is relatively short and they can be installed quickly.
- They are quick starting (as low as 10 s), often by remote control.
- They are smooth running and have a capacity factor (percent of time the unit is operating at full power) of 96 to 98 percent.
- They can use a wide variety of liquid and gaseous fuels including gasified coal and synthetic fuels.
- They are subject to fewer environmental restrictions than other prime movers.

Figure 10.1 illustrates a simple cycle gas turbine. The compressor raises the pressure of inlet air 15 to 25 times. The work required by the compressor appears in the flow in the form of increased temperature. The discharge temperature of the compressor is about 750 to 870°F (400 to 465°C). The combustors burn the fuel to increase the temperature of the compressed air to between 2500 and 2600°F (1370 to 1427°C). The turbine nozzles (stationary blades) convert the high-enthalpy air to high velocity. The turbine buckets (moving blades) convert this energy into rotary motion. The turbine discharge temperature is around 900 to 1180°F (482 to 638°C).

The categories of gas turbines are:

1. Industrial heavy-duty gas turbines
2. Aircraft-derivative gas turbines
3. Medium-range gas turbines
4. Small gas turbines

The efficiency of modern gas turbines has reached 43 to 44 percent with a firing temperature (inside the combustors) of 2500°F (1371°C). The limiting factor for the efficiency of the gas turbine is the metallurgy of the first stage of moving blades in the turbine. New

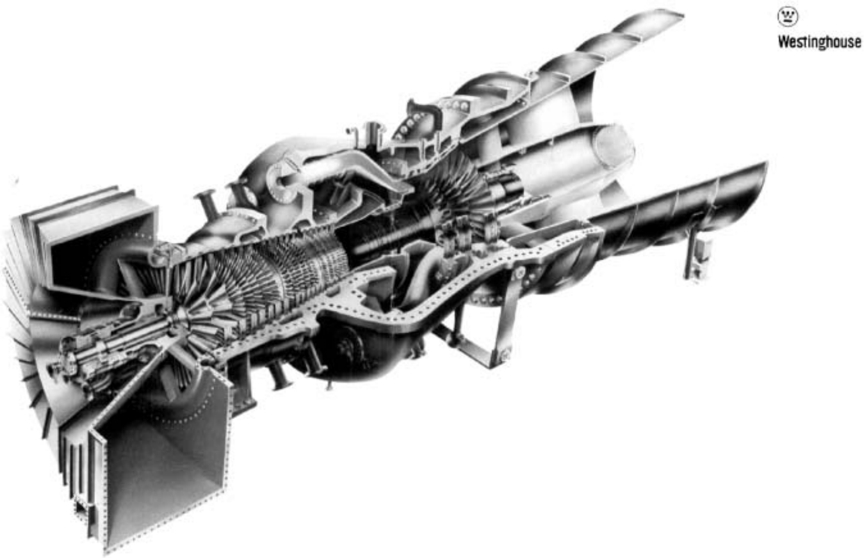


FIGURE 10.1 Combustion turbine, Model CW251B11/12.

The combustion turbine is a single shaft, two-bearing, solid coupling, simple cycle unit containing:

Multistage (19) axial-flow air compressor featuring:

- Variable inlet guide vanes.
- Horizontally split casing giving access to internal parts.
- Individually removable stainless steel blading.
- Accessible pressure-lubricated, pivoted-pad journal bearing.
- Double acting Kingsbury-type thrust bearing.
- Cold-end drive with solid coupling to main reduction gear.

Combustion system including the following:

- Eight can-type combustors in a circular array.
- Combustors removable with cylinder cover in place.
- Optional multiple fuels capability.
- Ignition system with retractable igniters.

Three-stage reaction-type turbine featuring:

- Horizontally split casing giving access to internal parts.
- Alloy turbine blades individually removable.
- Cooled by air-to-air cooler, with cooling air filtered.
- Individual first-stage vanes removable with cylinder cover in place.
- Accessible pressure-lubricated, pivoted-pad journal bearing.
- Low loss axial-exhaust system ideal for waste heat applications.

air-cooling methods and breakthroughs in the metallurgy of turbine blades allowed gas turbines available in research laboratories today to operate at 2800 to 3000°F (1538 to 1649°C). These gas turbines have higher efficiency than the modern gas turbines used in industry. Regeneration* has lowered the heat rate.† However, the best heat rate has been achieved by combining the gas turbine cycle with a steam turbine cycle. The arrangement is called *combined cycles.* Its heat rate is around 5000 to 7000 Btu/kWh. The efficiency of a gas turbine is affected by the firing temperature and pressure ratio across the compressor. For every 100°F (56°C) increase in firing temperature, the work output and efficiency increase by 10 percent and 1.5 percent, respectively.

Figures 10.2 and 10.3 illustrate a performance map of a simple-cycle and a regenerative cycle gas turbine as a function of pressure ratio and turbine inlet temperature. The pressure ratio has the opposite effect in a regenerative cycle compared to that experienced in a simple cycle. Regenerators can increase the efficiency of a modern gas turbine by about 15 to 20 percent. The optimum pressure ratio for a modern regenerative system is about 7:1 compared to 18:1 for a simple cycle gas turbine.

THE BRAYTON CYCLE

The Brayton cycle governs the behavior of gas turbines. Figure 10.4 illustrates an ideal Brayton cycle. It has two adiabatic-reversible (isentropic) processes and two constant-pressure processes.

*Regeneration consists of using a heat exchanger that recovers the heat from the air being discharged from the turbine. The temperature of the air discharged from the turbine is around 900 to 1180°F (482 to 638°C).

†The heat rate is the inverse of the efficiency (1/efficiency). It represents the amount of heat consumed (in Btu) to generate 1 kWh.

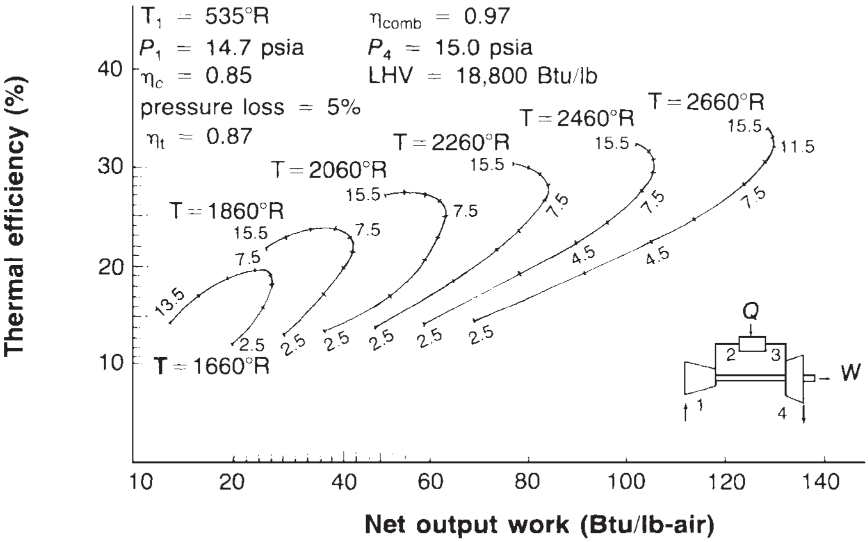


FIGURE 10.2 Performance map of a simple cycle.

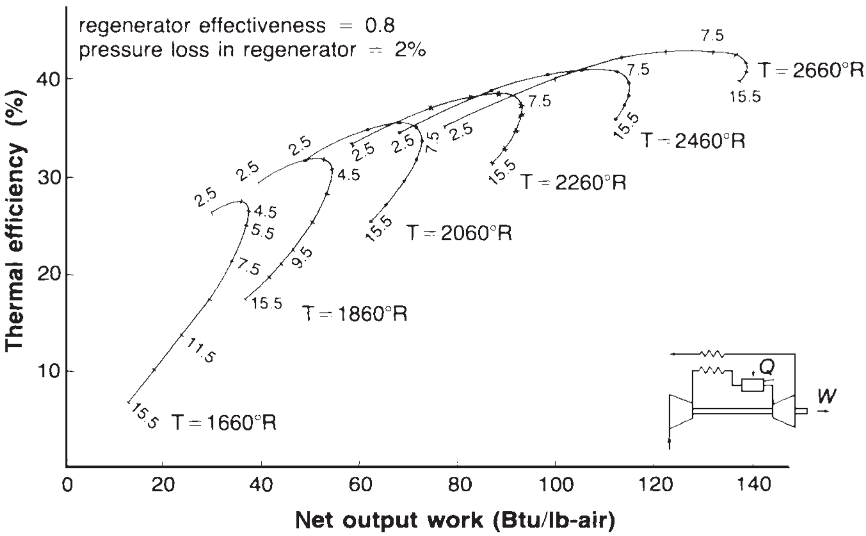


FIGURE 10.3 Performance map of a regenerative cycle.

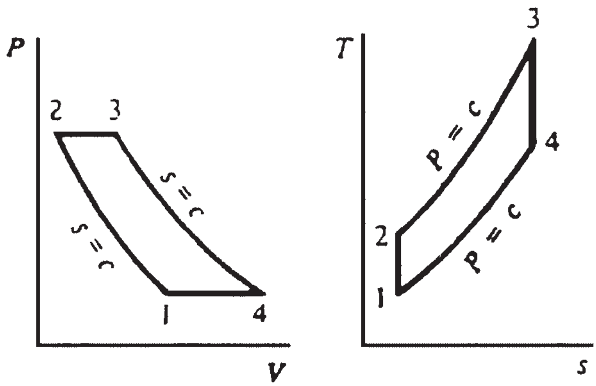


FIGURE 10.4 P-V and T-s diagrams of an ideal Brayton cycle.

The work done in the turbine W_T is equal to the rate of change of its enthalpy. Thus,

$$\dot{W}_T = \dot{H}_3 - \dot{H}_4 = \dot{m}(h_3 - h_4) \tag{10.1}$$

where $\dot{H}$ = total enthalpy of flowing gas, Btu/h or W
h = specific enthalpy, Btu/lb_m or J/kg
$\dot{m}$ = mass rate of flow of gas, lb_m/h or kg/s

Figure 10.5 illustrates a simple-cycle, two-shaft gas turbine. The power turbine, also known as the *low-pressure turbine,* operates on a different shaft than the high-pressure turbine and compressor. This feature allows the power turbine to drive a load at a wide range of speeds. Thus, the two-shaft machines are suitable for applications requiring variable speed.

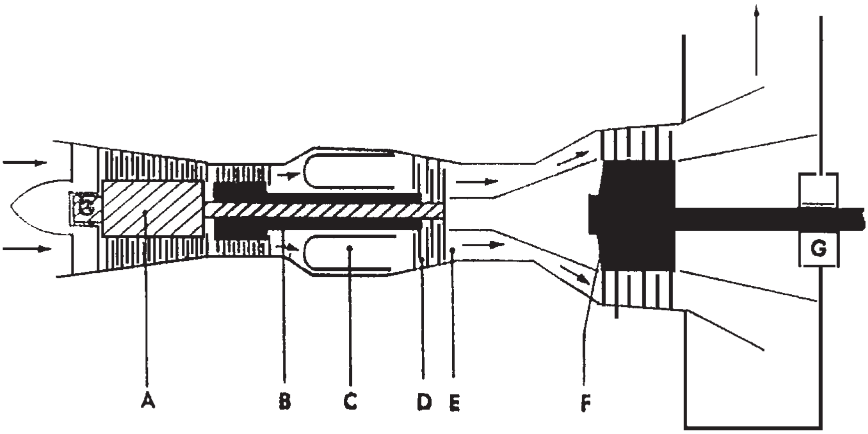


FIGURE 10.5 Dual-shaft gas turbine. *A:* LP compressor; *B:* HP compressor; *C:* combustors; *D:* HP compressor turbine; *E:* LP compressor turbine; *F:* power turbine; *G:* bearings.

The portion of the gas turbine consisting of compressors, combustors, and high-pressure (HP) turbine is called the *gas generator.* All the power developed by the HP turbine is used to drive the compressors. The requirements for starting this gas turbine are less than the ones for a single-shaft gas turbine. The reason is the reduced inertia of the spool carrying the compressor and HP turbine.

The ideal (isentropic) efficiency and specific work of a gas turbine are given by:

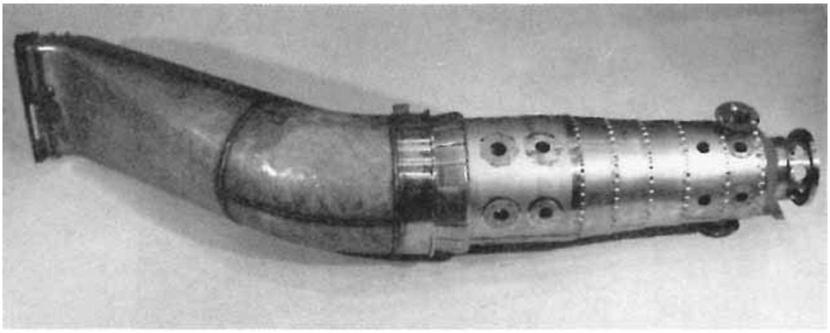
$$\eta_{\text{th}} = 1 - \frac{1}{r_p^{(k-1)/k}}\,; \qquad \frac{\dot{W}_n}{\dot{m}} = c_p\left[T_1\,(1 - r_p^{(k-1)/k} + T_3\left(1 - \frac{1}{r_p^{(k-1)/k}}\right)\right] \tag{10.2}$$

$$r_{pT} = \frac{P_3}{P_4}; \quad k = \frac{c_p}{c_v}; \quad \frac{T_3}{T_4} = r_{pT}^{(k-1)/k}$$

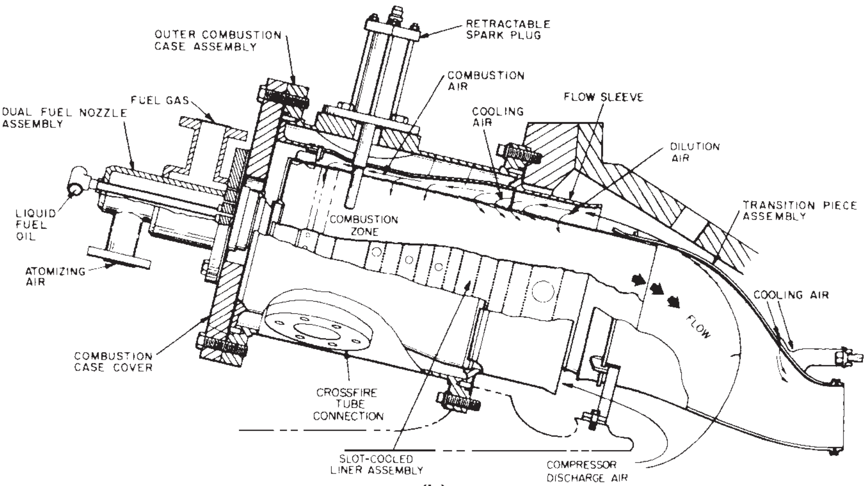
INDUSTRIAL HEAVY-DUTY GAS TURBINES

Industrial heavy-duty gas turbines entered the market in the early 1950s. These ground-based units did not have restrictions on weight and space. Their design characteristics included heavy-wall casings, sleeve bearings, large-diameter combustors, thick airfoil sections for moving and stationary blades, and large frontal areas. The pressure ratio for these gas turbines increased from 5:1 for earlier units to 15 to 25:1 for modern units. The turbine inlet temperature for a modern unit is around 2000 to 2500°F (1093 to 1371°C). Projected temperatures approach 3000°F (1649°C) and when achieved, would result in a significant increase in the efficiency of these machines. The industrial heavy-duty gas turbines normally use axial-flow compressors and turbines. In most North American designs, the combustors are can-annular as shown in Figs. 10.6(*a*) and 10.6(*b*). European designs use single-stage side combustors as shown in Fig. 10.7. The combustors of these units normally have heavy walls and are very durable. The liners are designed to produce low smoke and low NO_X* emissions. Most

*NO_X is a term used to describe the mixture of NO and NO_2.



(a)



(b)

FIGURE 10.6 (*a*) Can-annular combustor with transition piece. (©*Rolls-Royce Limited*) (*b*) A typical diffusion flame, can-annular, reverse-flow combustor. (*Courtesy General Electric Company*)

of these units have dual fuel flexibility. The velocity of the inlet air drops in the large frontal areas resulting in a reduction of air noise. The auxiliary equipment includes heavy-duty pumps and motors that have been tested for long hours. Heavy-duty governors are also used in the control system. Electronic governors are being used in some newer models. The following are the advantages of heavy-duty gas turbines:

- High availability
- Long life
- Slightly higher efficiencies when compared with other types of gas turbines
- Significantly lower noise levels than aircraft-type gas turbines

These machines are used normally in electric utilities to deliver base load power.

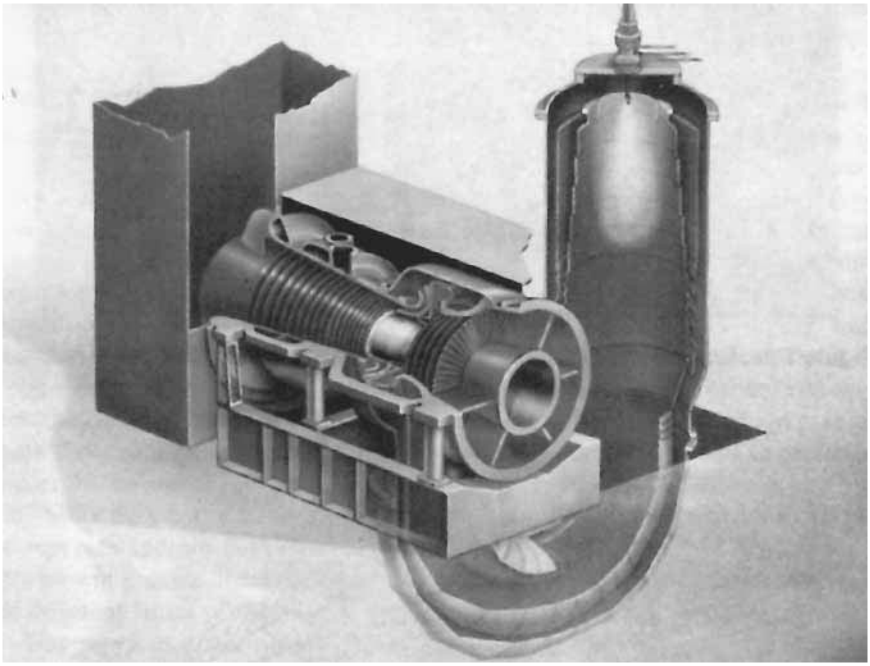


FIGURE 10.7 Side combustor can. (*Courtesy of Brown Boveri Turbomachinery, Inc.*)

AIRCRAFT-DERIVATIVE GAS TURBINES

Jet gas turbines consist of an aircraft-derivative gas generator and a free-power turbine. The gas generator produces the gas energy or gas horsepower. It consists of a compressor, combustors and a turbine. The turbine generates sufficient power to drive the compressor only. The combustion gas products leaving the gas generator are around 30 psi (206 kPa) and 1100°F (593°C). The free-power turbine converts the thermal energy in the gas to mechanical energy (torque x rotational speed) or brake horsepower. This mechanical energy is used to drive the load (see Fig. 10.8).

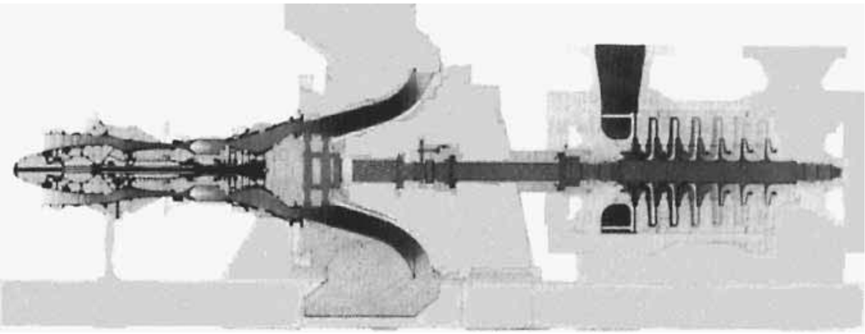


FIGURE 10.8 Aircraft-derivative gas turbine driving a centrifugal gas compressor. (©*Rolls-Royce Limited*)

Aircraft-type turbines are mainly used in the gas transmission industry and as peaking units in power plants. These are their main benefits:

- Relatively low installation cost
- They can easily be operated unattended by remote control due to the following reasons:
  - Their auxiliary systems are not complex.
  - They do not require water cooling (oil-to-air heat exchangers are used for cooling).
  - Their starting device, which is normally a gas expansion motor, requires little power.
  - Their performance can be monitored remotely. Maintenance is initiated upon degradation in performance.

MEDIUM-RANGE GAS TURBINES

Medium-range gas turbines are rated between 5000 to 15,000 hp (3.7 to 11.2 MW). These units have relatively high efficiency at part-load operation. The gasifier (section that generates the hot gas) operates at maximum efficiency, while the power turbine operates at variable speed. The compressor has normally 10 to 16 stages. Its pressure ratio (discharge pressure/inlet pressure) is around 5 to 11. Most American manufacturers use can-annular (5 to 10 combustor cans mounted on a circular ring) or annular-type combustors. European manufacturers normally use side combustors. The turbine inlet temperature of most European designs is normally lower than in American counterparts. Most gasifiers use a 2 to 3 stage axial turbine. Its first-stage nozzles (stationary blades) and buckets (moving blades) normally are air-cooled. Most power turbines have one or two stages.

These units are normally used on offshore platforms and in petrochemical plants. Regenerators are used with these turbines to improve their efficiency.

SMALL GAS TURBINES

Small gas turbines are rated below 5000 hp (3.7 MW). Their design is similar to the larger turbines discussed earlier. However, they normally use centrifugal compressors or combinations of centrifugal and axial compressors and radial-inflow turbines. These units have an efficiency of around 20 percent due to the following reasons:

- Centrifugal compressors have lower efficiency than their axial counterparts.
- The turbine inlet temperature is limited to around 1700 °F (927°C) due to lack of blade cooling.

The efficiency of these units can be improved by recovering the exhaust heat from the turbine.

MAJOR GAS TURBINE COMPONENTS

Compressors

Gas turbines use axial and centrifugal compressors. Small gas turbines use centrifugal compressors while all the larger ones use axial compressors.

Axial-Flow Compressors. Axial-flow compressors increase the pressure of the fluid by accelerating it in the rotating blades and then diffusing* it in the stationary blades. A compressor stage consists of one row of stationary blades and one row of moving blades. An additional row of fixed blades (inlet guide vanes) is normally installed at the inlet to the compressor to direct the air at the desired angle to the first-stage of rotating blades. An additional diffuser is installed at the compressor discharge. It diffuses the fluid further before entering the combustors. Figure 10.1 shows a 19-stage axial flow compressor. The overall pressure increase across a compressor of a modern gas turbine varies between 20:1 and 40:1. These compressors are generally more efficient than centrifugal compressors. They are also usually much smaller and run at higher speeds.

Centrifugal Compressors. Figure 10.9 illustrates the impellers of a centrifugal compressor. Air is taken at the center or "eye" of the rotor. It is accelerated by the blades due to high rotational speeds of the rotor and forced radially out of the rotor at high velocities. The air is then received by the diffuser, which converts the high velocity to high pressure.

A single compressor stage consists of an impeller mounted on the rotor and a diffuser mounted in the stator. The air enters the compressor at the inducer (see Fig. 10.10). It goes through a 90º turn and is discharged into a diffuser which normally has a vaneless space followed by a vaned section. The air leaves the diffuser and enters a scroll or collector. The pressure increase per stage of a centrifugal compressor varies between 1.5:1 and 12:1. Centrifugal compressors have lower efficiency than axial-flow compressors. However,

*A diffuser is a component of increasing cross-sectional area. The fluid pressure increases across it due to decrease in velocity.

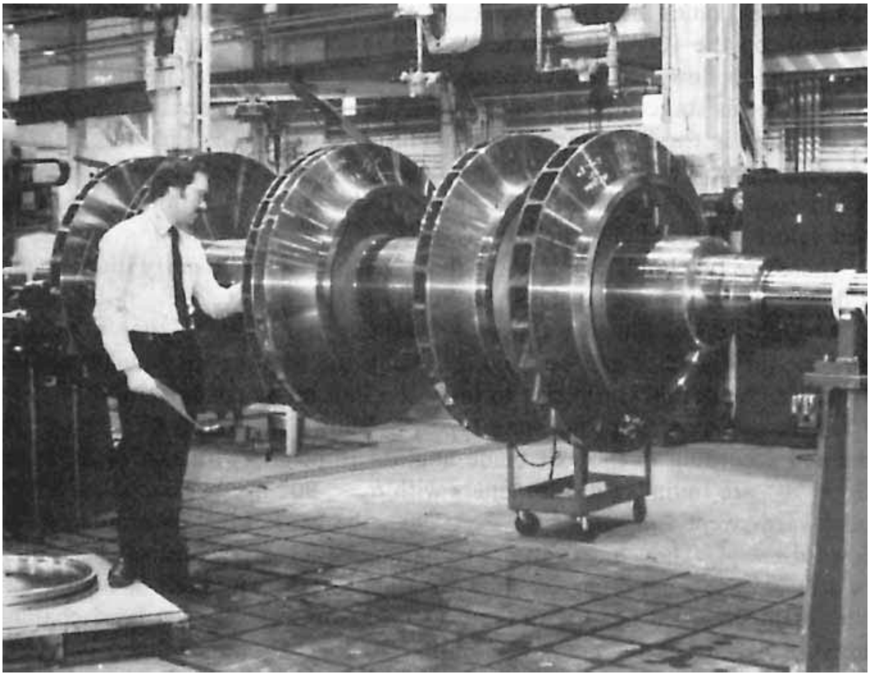


FIGURE 10.9 Closed impeller. (*Courtesy Elliott Company, Jeannette, PA*)

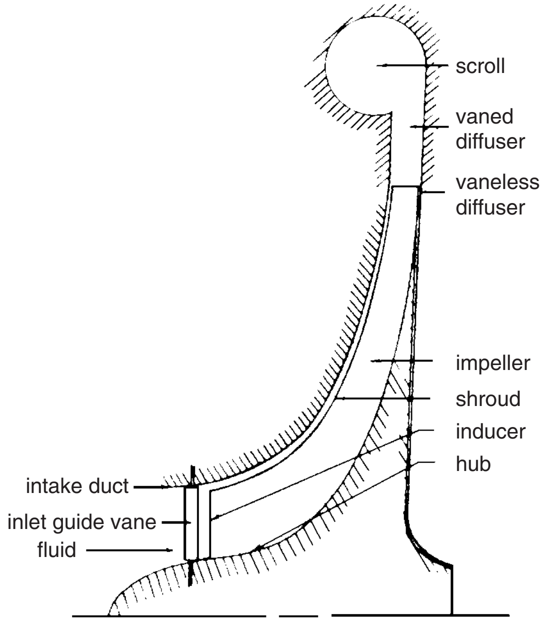


FIGURE 10.10 Schematic of a centrifugal compressor.

they are not as prone to a reduction in efficiency due to the build-up of deposits as in axial-flow compressors. Their main advantages are simplicity, strength, and short length.

Compressor Materials

The compressor casings are usually made of cast iron or aluminum alloy. The rotors are usually made of good-quality ferrite steel, and the compressor blades will be stainless steel or titanium alloys.

Two-Stage Compression

The compression process requires less work if heat is removed from the gas during the process. This improves the efficiency of the gas turbine. A two-stage compression is often used with an intercooler between the stages (see Fig. 10.11).

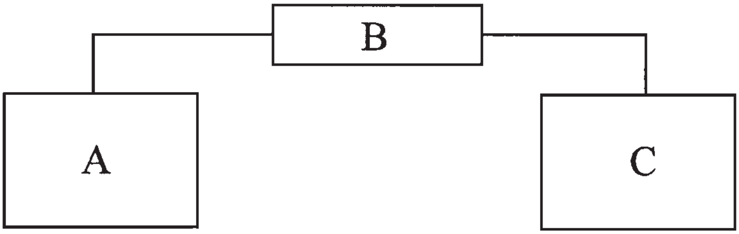


FIGURE 10.11 Two-stage compression. *A:* compressor; *B:* intercooler; *C:* compressor.

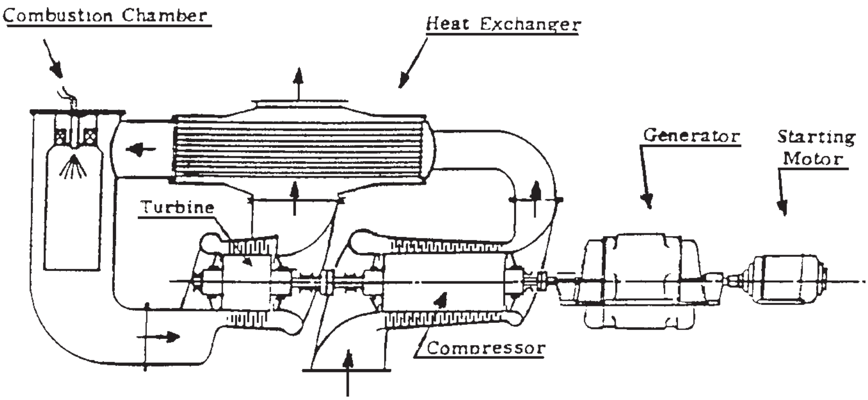


FIGURE 10.12 Gas turbine with regenerator.

Regenerators

In simple gas turbines, the gases exhausted from the turbine are still at a high temperature, 900 to 1180°F (482 to 638°C). The thermal efficiency of the gas turbine will improve if some of the heat in the exhaust gases is transferred to the compressed air before the air enters the combustor. This is accomplished by adding a heat exchanger called a *regenerator* to the basic cycle (see Fig. 10.12).

The regenerator (see Fig. 10.13) is a shell-and-tube heat exchanger having the turbine exhaust gases flowing in the tubes or on the shell side. The temperature of the exhaust gases from the turbine is reduced to 500°F (260°C) by transferring heat to the air in the regenerator. The air enters the regenerator at 392°F (200°C) and leaves at about 698°F (370°C). The regenerator can recover up to 75 percent of the exhaust heat, resulting in increase in efficiency.

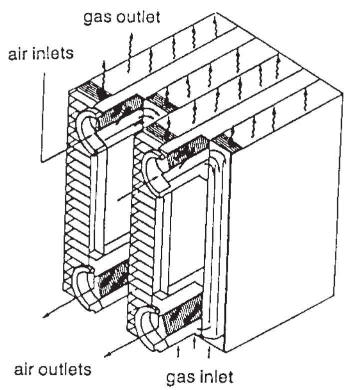


FIGURE 10.13 A typical plate-fin industrial regenerator for gas turbines.

Heavy-duty regenerators are used in large gas turbines in the 5000 to 100,000 hp (3.7 to 74.6 MW) range. They increase the efficiency of the unit by reducing the fuel consumption by up to 30 percent. Despite this increase in efficiency, regenerators are only used by a small number of manufacturers for these reasons:

- The increase in efficiency caused by using regenerators decreases steadily as the unit is operated due to build-up of deposits inside the regenerator.
- Regenerators are only used by turbines having low pressure increase across their compressors. The reason for this is that gas turbines having a large pressure increase across their compressors will also have a large temperature increase across them (the work required to increase the pressure across a compressor is proportional to the temperature increase across it). Since the temperature of the gas leaving the turbine is around 482°C (900°F), units having large pressure increase across their compressors will have limited benefit from a regenerator because the exit temperature of the compressor will approach the exit temperature of the turbine.
- Regenerators have relatively high cost, space, and maintenance requirements.

Combustors

The purpose of the combustor is to increase the temperature of the high-pressure gas. There is a slight pressure drop across the combustors. The four categories of combustors are:

- Tubular (side combustors)
- Can-annular
- Annular

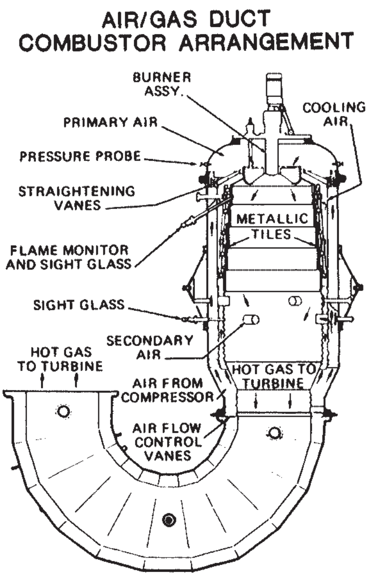


FIGURE 10.14 A typical single-can side combustor for an industrial turbine. (*Courtesy Brown Boveri Turbomachinery, Inc.*)

Tubular (side combustors). These combustors (see Figs. 10.7 and 10.14) are normally installed on large European industrial turbines. Their advantages are:

- Simple design
- Ease of maintenance
- High longevity

They could be of a "straight-through" or "reverse-flow" design. In the reverse-flow type, air enters the annulus between the combustor can and the housing. This design has minimal length.

Can-Annular and Annular. Most industrial heavy-duty gas turbines designed in the United States use can-annular combustors [see Figs. 10.6(*a*) and (*b*)]. Can-annular (known also as *tubo-annular,* Figs. 10.15 and 10.16) and annular (Fig. 10.17) combustors are used in aircraft engines due to their favorable radial and circumferential

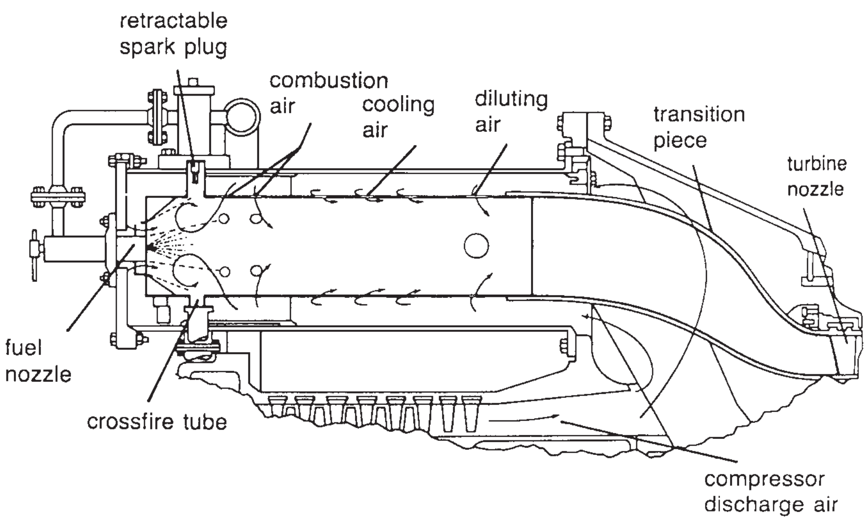


FIGURE 10.15 Tubo-annular or can-annular combustor for a heavy-duty gas turbine. (*Courtesy of General Electric Company*)

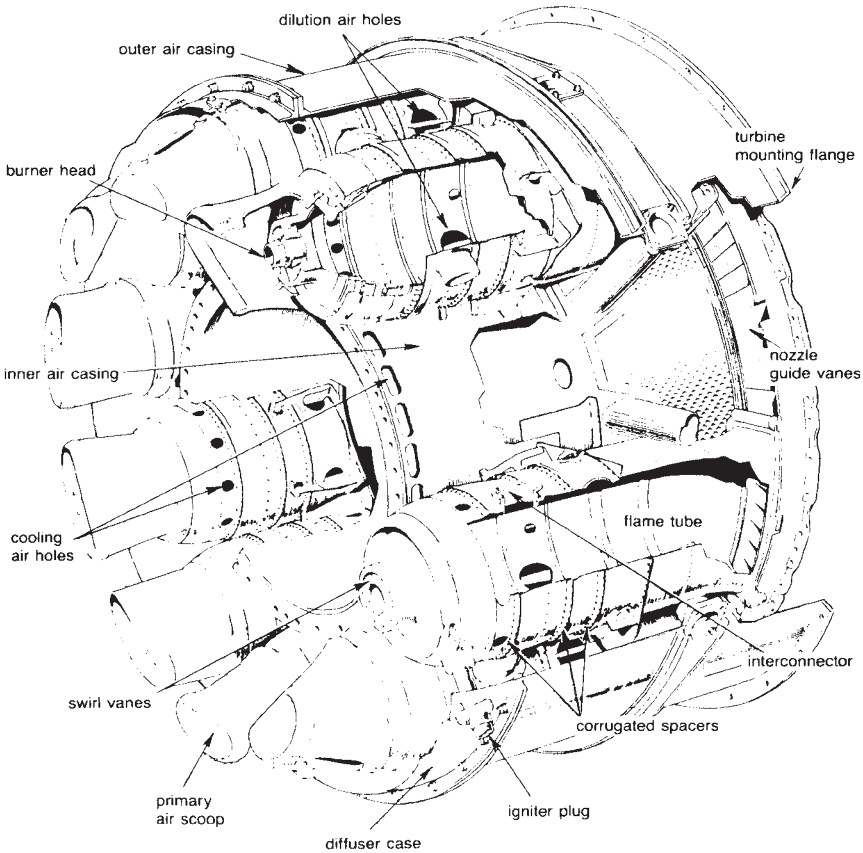


FIGURE 10.16 Tubo-annular combustion chamber for aircraft-type gas turbines. (©*Rolls-Royce Limited*)

profiles. These designs are suited for the large number of fuel nozzles employed in these applications. Annular combustors are used more commonly in applications having higher temperatures and low-heat-content (low-Btu) gases.

There are straight-through and reverse-flow can-annular combustors. The can-annular cans used in the aircraft industry are of the straight-through design. The reverse-flow design is normally used in industrial engines. Annular combustors are normally straight-through design.

Combustor Operation. In multiple-type combustors, there is a fuel supply to each flame tube, but there are only a couple of igniters for all the tubes. When ignition occurs in the flame tubes having the igniters, the crossfire tubes takes the hot gases from the hot flame tube to ignite the remainder. This occurs in a matter of one second. Once the flame detectors confirm stable ignition, the igniter will shut down. The manufacturers of gas turbines confirm that any fuel can be used if the necessary changes are made to the fuel system.

Turbines

Axial-flow and radial-inflow turbines are used in gas turbine applications. However, more than 80 percent of gas turbines use axial-flow turbines.

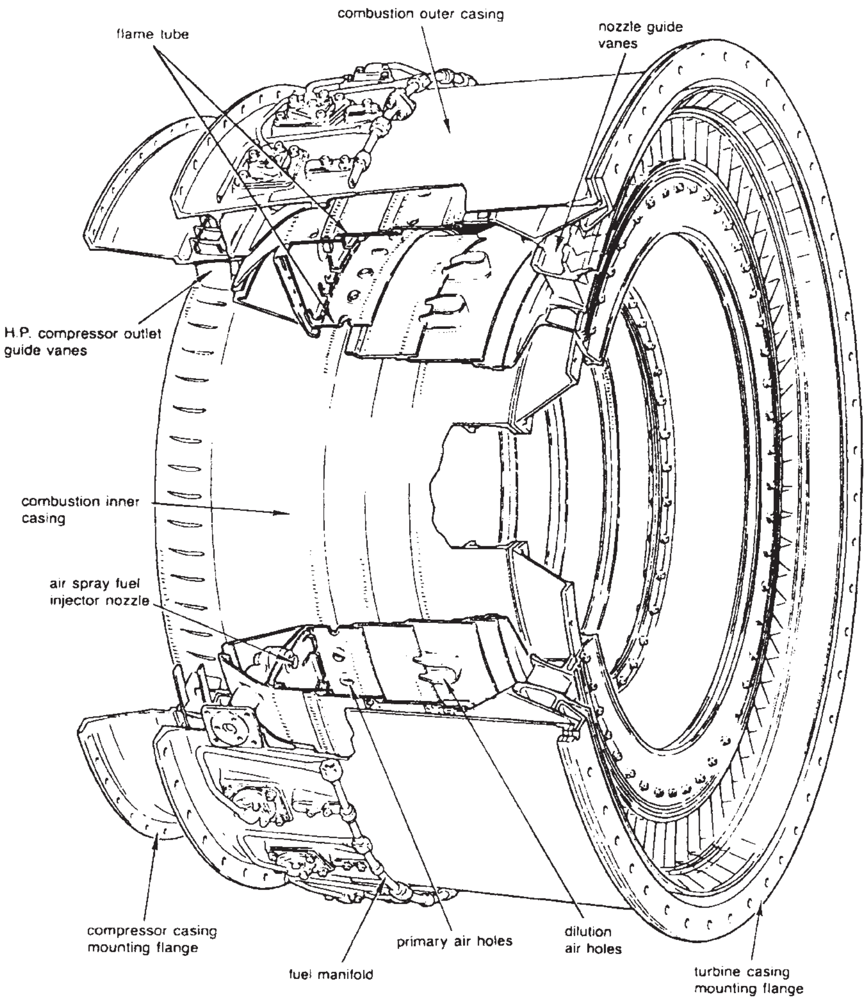


FIGURE 10.17 Annular Combustion Chamber. (©*Rolls-Royce Limited.*)

Axial-Flow Turbines. The flow in an axial-flow turbine (Fig. 10.18) and its counterpart, the axial-flow compressor, enters and leaves in the axial direction. These turbines can be of the impulse type or the reaction type. In an impulse turbine, the enthalpy drops entirely (the energy available in the high temperature and pressure is converted into velocity) in the nozzles (stationary blades). Thus, the velocity of the gas entering the rotor is very high. In a reaction turbine, the enthalpy drops in the nozzles and the buckets (moving blades).

Radial-Inflow Turbine. The radial-inflow turbine, or inward-flow radial turbine, consists of a centrifugal compressor having reverse flow and opposite rotation. These turbines are used for smaller loads and over a narrower operating range than the axial turbine. Axial turbines are normally suited for aircraft and power generation applications. However, they are much longer than radial turbines. This makes them unsuitable for certain applications. Radial turbines are normally used for turbochargers and in some types of expanders.

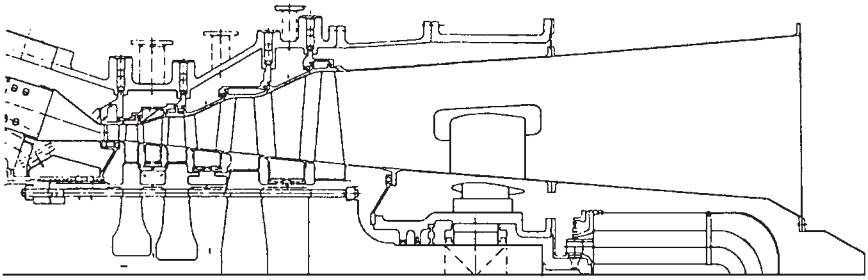


FIGURE 10.18 Schematic of an axial-flow turbine. (*Courtesy of Westinghouse Electric Corporation.*)

Heat Recovery Steam Generators

Most of the heat available in the exhaust gases [normally around 482 to 638°C (900 to 1180°F)] of a gas turbine can be recaptured in a heat recovery steam generator (HRSG). The steam can be used in the following applications:

- To drive a steam turbine in a combined cycle* plant
- For heating purposes in a cogeneration plant
- For a process in an industry such as a petrochemical plant

The HRSG (Fig. 10.19) is a counterflow heat exchanger used to generate steam by convection.

The following are its main components:

- The superheater: This is the first component exposed to the exhaust gases from the gas turbine. It superheats the saturated steam leaving the boiler.

*A combined cycle consists of a gas turbine working in conjunction with a steam power plant through an HRSG.

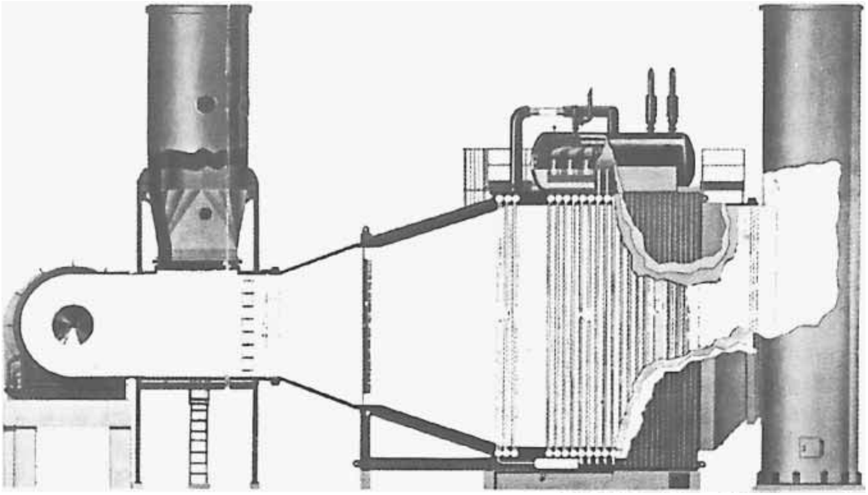


FIGURE 10.19 Supplementary fired exhaust gas steam generator. (*Courtesy of Henry Vogt Machine Company.*)

- The boiler: This component is exposed to the hot gases leaving the superheater. It provides the latent heat required to evaporate the saturated water leaving the economizer.
- The economizer: This component is exposed to the hot gases leaving the boiler. It provides the heat required to raise the temperature of the subcooled water entering the HRSG to saturation.

TOTAL ENERGY ARRANGEMENT

Gas turbines have been used in cogeneration and combined cycles plants to produce electricity and steam. In some cases, the steam is used in absorption chillers to produce cold water, which is used for cooling buildings with the aid of a cooling tower. This is known as a *total energy arrangement* due to the generation of steam, electricity, and cold water.

GAS TURBINE APPLICATIONS

Gas turbines have been used to produce power as well as an engine to drive pumps, compressors, emergency equipment, etc. It is common to use gas turbines in power plants and hospitals to produce instant emergency power for essential services when the main power supply is interrupted. Gas turbines are ideal for use as an unmanned and remotely controlled unit that can be started by a telephone or radio link.

COMPARISON OF GAS TURBINES WITH OTHER PRIME MOVERS

Modern gas turbines compare very favorably with other machines on the grounds of fuel consumption, efficiency, and power/mass/size ratios. Gasoline engines operating on the Otto cycle have efficiencies of 20 to 25 percent. The diesel and Rankine cycles (steam plant) have an efficiency of 30 to 35 percent. The modern gas turbine, which operates on the Brayton cycle, has an efficiency of 44 percent.

REFERENCES

1. Boyce, Meheran P., Gas Turbine Engineering Handbook, Golf Publishing Company, Houston, Tex., 1995.

2. El-Wakil, M. M., Power Plant Technology, McGraw-Hill, New York, 1984.